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A grand challenge for membrane desalination: More water, less carbon

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ABSTRACT

The decarbonisation of membrane desalination is a grand challenge due to the competing demands of more water for a thirsty world and the urgent need to reduce carbon emissions to mitigate climate change. This paper is a review of some developing strategies that could lead to lower energy use and thereby reduce the carbon foot print of desalination. Each strategy brings benefits along with technical challenges that are research opportunities.

The use of very low energy 'engineered biofilms' coupled with biomimicry control of biofouling could almost eliminate pretreatment energy. Improved membranes based on 'water channels' could contribute to reduced energy demand but high flux operation will need novel mass transfer control and will be constrained by module engineering. Significant energy benefits could come from combining seawater RO with wastewater reclamation using forward osmosis and pressure-retarded osmosis (PRO), although fouling by the wastewater stream requires special attention. The overall potential of the novel pretreatments, membranes and post-treatments is to more than halve the net energy of RO desalination. However there would be significant trade-offs to achieve this level of decarbonisation. The application of renewable energy is considered in the context of a membrane-enabled osmotic battery using PRO for discharge and advanced RO for recharge. Finally, low energy desalination for agriculture is being developed using novel applications of forward osmosis.

1. Introduction

There is overwhelming agreement that emissions of greenhouse gases (GHGs) must be reduced significantly, and eventually to zero, over the next few decades to mitigate climate change. Decarbonisation will be required over all sectors, including water supply. At the same time our increasingly thirsty world is turning to seawater and brackish water desalination to augment supplies. Desalination of seawater by reverse osmosis (SWRO) is now the dominant technology and over the past 50 years the energy demand has dropped by a factor of 5 so that the reverse osmosis step is currently approaching 2 times the thermodynamic minimum [1,2]. However as the total installed capacity approaches 100 megatonnes/day (currently > 60 Mte/day with 10 to 15% annual growth rate) the total energy usage approaches 100 TWh/year (assuming an energy demand of 3.0 kWh/m^3 for state of the art SWRO [2]). In terms of GHG emissions this is in the range 60 to 100 Mte CO_2 per year, potentially growing at 10 to 15% p.a. While this is currently a modest component of the global separation technology impact it could change as other industries decarbonise and SWRO continues to grow in application. Clearly 'business as usual' for SWRO desalination is not an option. In response this paper discusses various strategies to lower energy demand and to decarbonise RO desalination. It is a selective review based largely on the author's experience and interests; more comprehensive reviews of the status and future of desalination and membranes are available elsewhere (for example [1–4]).

2. Desalination RO energy and strategies to decarbonise

Modern seawater RO plant produce water at an overall energy demand of 3.0 to 3.5 kWh/m^3 where the RO step is of the order 2.2 kWh/m^3 [2] and low pressure membrane pretreatment is of the order 0.3 kWh/m^3 [5], that is the membrane components are about 2.5 kWh/m^3. As we will see it should be feasible to halve that value by current developments and changes to the process. The topics of interest are as follows:

(i) mitigation of RO membrane fouling, particularly biofouling, by low energy 'bio'-pretreatment and biomimicry control;
(ii) improvements in RO membranes and modules; and
(iii) low energy processing by hybridisation with FO/PRO using alternative water sources.
(iv) Related topics also discussed are;

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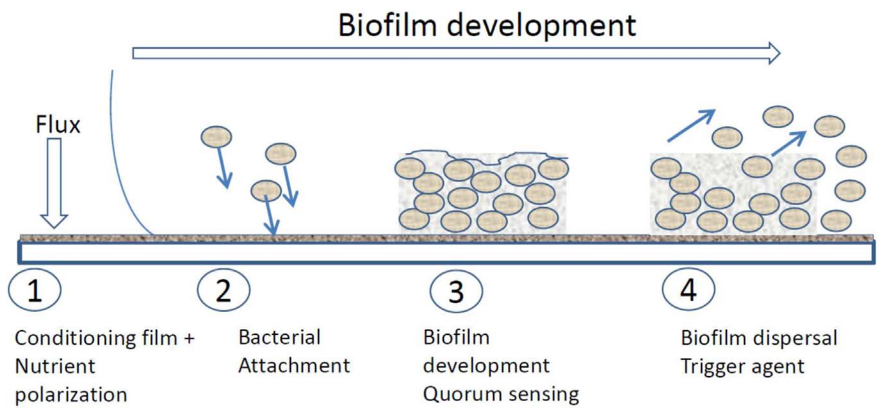


Fig. 1. Evolution of biofouling on a membrane – steps 1 to 4.

(v) a membrane-enabled osmotic battery to facilitate renewable energy usage;
(vi) low energy desalination for agriculture exploiting osmotic gradients.

2.1. Mitigating fouling of RO membranes

Membrane fouling increases the energy required for desalination either by decreasing productivity (flux) or increasing the required driving force (transmembrane pressure and feed channel deltaP); biofouling is a major issue [6]. The biofouling process involves several steps depicted in Fig. 1 that provide hints to (partial) prevention and cure. Nutrient concentration at the membrane surface (step 1) can be controlled by limiting the feed nutrients and its flux-induced polarization. Bacterial attachment (step 2) depends on incoming bacterial load although this is less important than the nutrient load that drives growth. Biofilm development is facilitated by quorum sensing trigger chemicals (step 3) and other triggers promote dispersal (step 4). Bioenabled fouling strategies being developed tackle steps 1, 3 and 4.

2.1.1. Low energy pretreatment

Pretreatment of seawater prior to RO desalination is considered essential. Potentially the most effective current approach is to use beachwells and recent developments and improved designs for beach and seabed galleries [7] make them more attractive at larger scale. However in some locations beachwells may not be feasible. Beachwells remove turbidity and, importantly, much of the assimilable organic carbon (AOC) [8] is removed by biological action within the beachwell matrix. The presence of nutrient AOC in RO feed water leads to biofouling (step 1) and related inefficiencies. We have shown in lab studies a direct correlation between organic nutrient concentration (enhanced by concentration polarization) and permeability decline [9]. Conventional SWRO pretreatment could involve media filters, low pressure UF and possibly dissolved air flotation (DAF). As currently operated none of these methods favours AOC removal by promoting 'engineered' biofilms. The industry is moving to UF pretreatment as it promises greater security [5]. However, as operated, UF involves frequent backwash and significant energy use ($\sim$0.3 kWh/m^3) contributing to the total energy demand for SWRO desalination. Conventional UF requires chemical cleaning, membrane replacement and/or maintenance. Its ability to remove turbidity is good but the extent of AOC removal is limited.

One approach to a low energy 'bio' pretreatment is depicted in Fig. 2 using gravity driven membranes (GDM). This is based on previous studies on river waters at EWAG [10]. Under gravity-driven deadend flow the flux stabilizes owing to a beneficial biofilm on the UF membrane surface and this is achieved without backwash or chemicals. We have found similar results are possible with seawater feed [11] and this gives water of low fouling potential at an energy demand of the order of 0.01 kWh/m^3. Fig. 2 also summarizes pilot-scale RO fouling and shows that the GDM can outperform commercial UF as a biofouling control. Of particular interest is the stabilized GDM flux of almost 20 l/m^2 h with a driving force of only 0.4 m (40 mBar) head due to control of the GDM biofilm structure by eukaryote predation [12]. One potential limitation of GDM pretreatment could be the larger footprint required, although our preliminary analysis suggests that it is not the case. Indeed due to the simplicity of the GDM it would be feasible to locate this type of pretreatment off-shore on barges. Similar beneficial 'bio' pretreatment for SWRO appears to be offered by biofiltration [13,14]. The bottom line could be an energy saving of the order of 0.3 kWh/m^3 in the overall desalination process.

2.1.2. Biomimicry control

However some degree of biofouling on the RO membrane is inevitable and another strategy, or partial cure, is to employ 'biomimicry' to interrupt biofilm growth on the membrane. Various chemical triggers are involved in biofilm development and this can be exploited to reduce biofouling. Quorum quenching has been successfully applied to disrupt quorum sensing triggers, such as AHL (Fig. 1, step 3), and control fouling in membrane bioreactors [15] and in recent studies on RO [16] we have shown that quorum quenching bacteria (QQB) and their enzymes can also delay fouling in a constant flux 'biofouling' RO system. Similarly biofilm dispersal (Fig. 1, step 4) is chemically triggered by agents such as nitric oxide and NO donors introduced into a biofouling RO system can also delay transmembrane pressure (TMP) rise [17]. Neither of these biomimicry strategies eliminates biofouling but such methods promise to improve biofouling control in RO, with consequent energy savings. One approach to strengthening biomimicry would be to combine it with other biocidal agents that act synergistically, as demonstrated in previous work [18].

2.2. Improvements in RO membranes and modules

The past decade has seen several innovations that promise to vastly improve the water permeability (A) of desalination membranes. These potential 'ultrapermeable membranes' (UPMs) include incorporation of Aquaporins [19,20], carbon nanotubes [21] and graphene materials [22]. The relevance of UPMs to desalination energy has been illustrated by the MIT group [23] who conclude that a 3 fold increase in A could decrease SWRO energy by $\sim$15% (this is conservative and the potential could be $\sim$20%) and brackish water energy by $\sim$40%. In addition higher fluxes would decrease the number of modules, and by implication, the deltaP of the process train, thereby lowering pumping energy. To achieve the full benefit of high permeability it would be necessary to operate UPMs at 'close to osmotic pressure' and this would require multistaging [1] or some form of batch operation with increasing feed pressure, such as Closed Circuit Desalination (CCD) [24].

The basis of the proposed UPMs are materials that provide selective

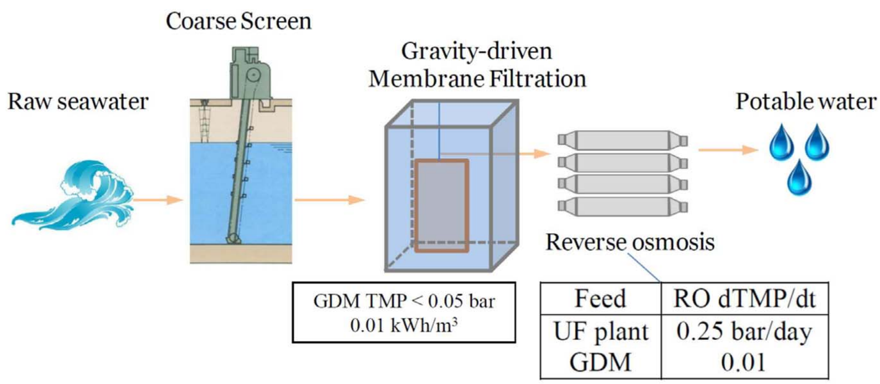


Fig. 2. Low energy pretreatment by gravity-driven membranes showing RO fouling control (details in [11,12]).

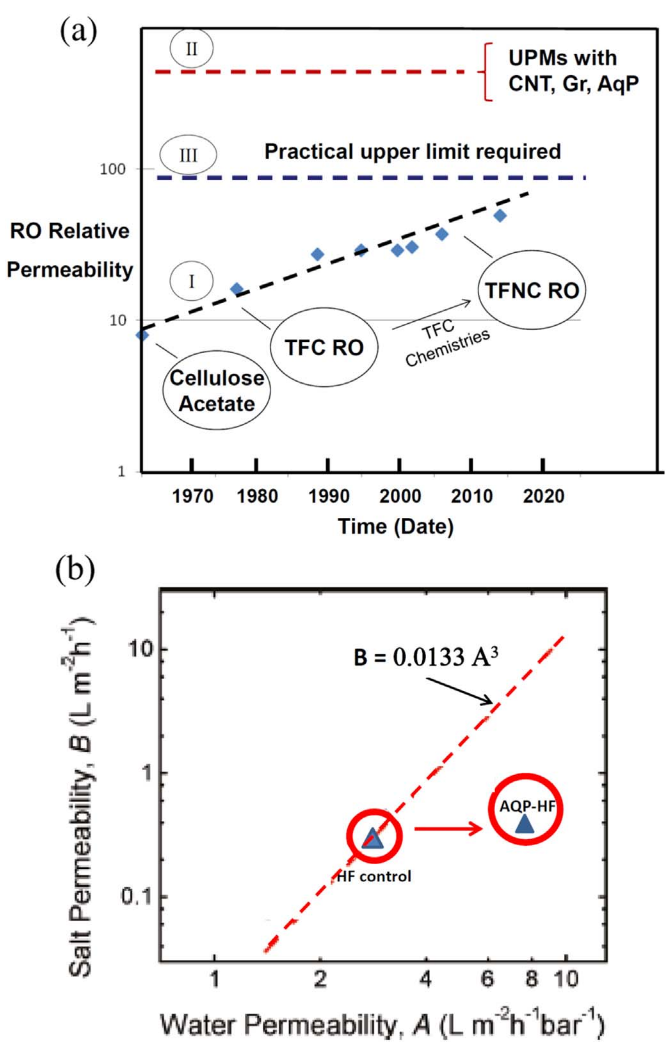


Fig. 3. (a) Evolution of RO membrane water permeability [4]. (Copyright Wiley-VCH Verlag: reproduced with permission). (b) Typical A vs B relationship (from [24]) and Aquaporin-enabled RO values [20].

water channels, and this is a paradigm shift away from current polymer-based RO membranes that transport by the solution-diffusion mechanism. Interestingly advances in permeability of current membranes have been significant over the past 50 years and follow a type of ‘Moore's Law’ with a doubling time every 10 years or so [4], see line I in Fig. 3(a). The question is, can this continue? A challenge for the conventional solution-diffusion membranes is the apparent link between A and B (salt permeability). The line, $B = 0.0133\ A^3$, in Fig. 3(b) from [25] was obtained from a wide range of hand-cast membranes. A similar link is found in the ‘upper-bound’ analysis of A and B values by Giese et al. [26]. This implies that significant improvements in A will tend to result in lower salt rejection. However membranes based on selective water channels should provide a way of stepping off the A/B trend line. For example in terms of evolving UPMs we have developed [19,20] Aquaporin-enabled thin film composite (TFC) membranes that combine the conventional polyamide TFC chemistry with Aquaporin vesicles that impart regions of high A and low B in the thin film. Fig. 3(b) shows that this membrane does ‘step-off’ the conventional A/B line with a doubling in A without change in B. Further advances in UPMs based on novel materials can be anticipated, trending to the ‘step-change’ line II in Fig. 3(a).

However could such membranes be used? The overall process of producing a quantum of pure water from a salty feed water through a membrane involves 4 distinct transfer steps (Table 1). Each step is potential limiting, so that having a very high A value (step 2) is not necessarily enough. For example considering step 3 the substrate surface porosity (pore size, spacing etc.) can significantly influence the actual A value relative to its intrinsic value [27]. So TFC support layer optimisation needs to match improvements in A. Both steps 1 and 4 are module related. For example, it is known that due to pressure gradients in feed and permeate channels the local driving force and flux across a membrane leaf in the spiral wound module (SWM) varies as simulated in Fig. 4 [28]; this pattern is also reflected in the foulant distribution [29]. These maldistributions could be greatly exacerbated by high flux (high A) operation. To overcome this may require novel designs of the SWM feed and permeate spacer and/or leaf geometry (length/width ratio etc.).

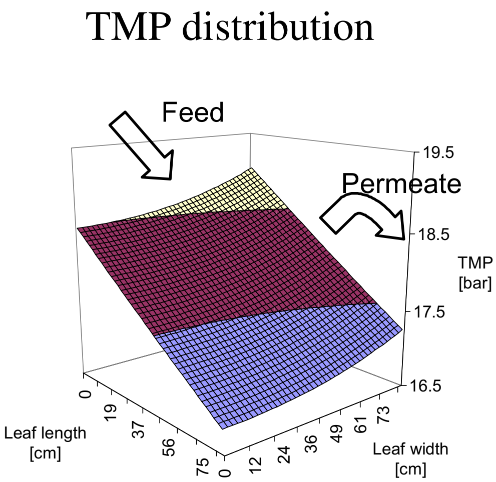
However probably the most limiting factor for UPMs operated at high flux will be step 1, concentration polarization (CP) and fouling. Even in the absence of fouling the CP generated by high flux could be limiting. This is because the CP modulus (M) is given by,

$$M = C_W/C_B = \exp(J/k) \tag{1}$$

where J is flux and k is the boundary layer mass transfer coefficient. So for a typical $M = 1.2$ in RO desalination an attempt to increase flux by $10\times$ would raise M to 6.0, which is impractical in terms of local osmotic pressure. Clearly increases in J require increases in k. The challenge is depicted in Fig. 5 for A values up to 100 l/m^2 h (50 to 100 × current values) for a range of k values. The typical current k value is about 100 l/m^2 h and this shows little improvement in water flux as A

Table 1
Transport steps through membrane and module.

Water transport step	Issue
1. Bulk to membrane surface.	Concentration polarization & fouling.
2. Transport through selective layer.	Membrane A value.
3. Transport through substrate layer.	Substrate porosity effect.
4. Permeate flow.	Permeate-side pressure drop.



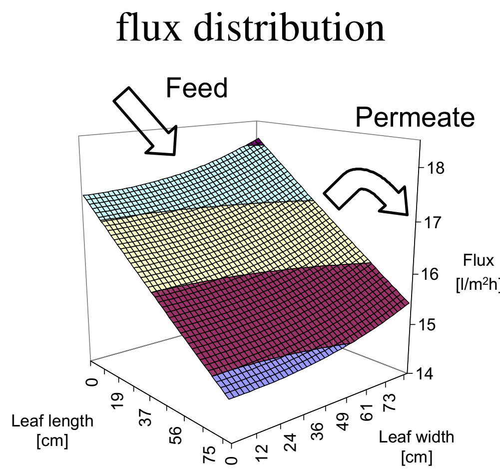


Fig. 4. TMP and flux distribution across a spiral wound module membrane leaf [28]. Note the elevated TMP and local flux at module inlet near the permeate tube.

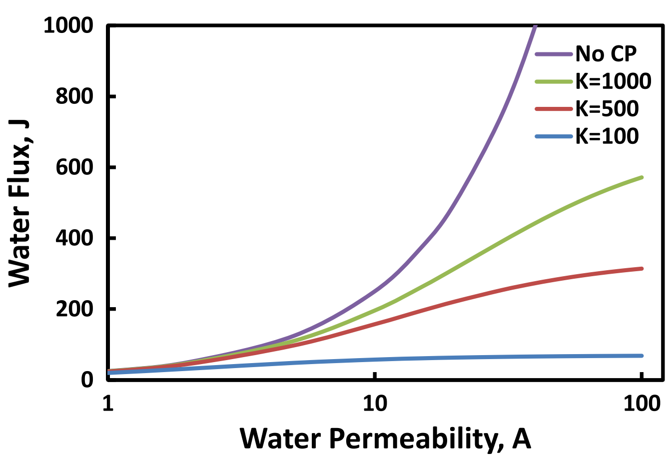


Fig. 5. Potential water flux versus membrane permeability A for range of mass transfer coefficients k. Basis: Flux J = A (ΔP − exp (J/k).ΔΠ), with ΔP = 50 bar, ΔΠ = 25 bar, complete retention, no fouling. Typically A = 1.0 to 2.0 l/m² h, k = 100 l/m² h (28×10^{-6} m/s).

increases.

To exploit UPMs it would be necessary to achieve 5 to 10 × current k values, and this implies reducing boundary layer thickness by up to 10 × without significant energy input. Boundary layer disruption by unsteady state shear may be effective. Strategies that have been successful in low pressure membrane processes can be considered, including two-phase flow and vibrations. Table 2 (adapted from [30]) summarizes the reported flux enhancements and estimated energy demand for various unsteady state shear techniques; an energy benchmark of 5 W/m² is proposed and this is 10% of the 50 W/m² based on assumed RO flux of 20 l/m² h and desalination energy of 2.5 kWh/m³ [2]. According to Table 2, two-phase flow with bubbles and vibrations (axial or lateral) have potential, although vibrations maybe more suited to hollow fibre modules and this requires UPMs based on external skinned TFC hollow fibres (not yet fully developed). Vibrations as used in the VSEP module are very effective for difficult feeds but tend to be too energy intensive for desalination and the concept has scale-up limitations. Table 2 suggests that mass transfer enhancements of 2 to 3, possibly 5 ×, maybe feasible via developments in modules and operation, using 2-phase (bubbles) and/or vibrations. For example Guha et al. [31] have recently described the localized generation of microbubbles at the surface of a RO membrane using a membrane-bound surface catalyst and hydrogen peroxide; very promising reductions in CP are reported. Similarly 'micro-nano' bubbles, generated in the feed stream, have been shown to enhance flux in high pressure RO [32]. Table 2 also identifies novel spacer design as a challenge for two-phase and vibratory systems. In this context 3D printing provides a way to explore novel spacer geometries [33] and we have recently developed a spacer with moving filaments that provides additional surface shear [34]. In summary, there are techniques being developed to improve boundary layer mass transfer to match some of the advances in material science and membrane permeability. However line III in Fig. 3(a) (Evolution of A) represents the conservative view that there will be a practical upper limit on useful permeability A (3 to 5 fold increase) imposed by module engineering. This will need to be achieved without increasing salt permeability B (as in Fig. 3(b)), implying the need to pursue 'water channel' membranes for next generation RO. In terms of the 'grand challenge' to decarbonise desalination the combined benefits of improved RO permeability and module efficiency could shave about 0.4 kWh/m³ (20% of 2.2 kWh/m³) from desalination energy demand.

2.3. Low energy by hybridisation and alternative water sources

It is well established [35] that RO-based water reclamation of wastewaters requires about 50% of the energy of SWRO. In terms of the water supply system this suggests that multiple reuse cycles of desalinated seawater, as exemplified by Singapore (Fig. 6), would reduce the net energy required for water production. By 2060 Singapore plans to produce up to 85% of its water supply via RO of which about 1/3rd will be SWRO and the balance WWRO.

However water reclamation offers additional energy saving

Table 2
Potential enhancements and estimated specific power for unsteady-state shear techniques (data from [30]).

Technique	Potential enhancement factor	Specific power (W/m²)[a]	Preferred module	Challenges
Two-phase flow (particles)	3-5 ×	To 0.25	FS or HF	Spacer design Membrane Integrity
Two-phase flow (bubbles)	2–5	To 5	FS or HF	Spacer design
Vibrations (axial/lateral)	2–10	To 0.6	HF	FS difficult Spacer design
VSEP	2–20	To > 100	FS	High energy Scale up

[a] Benchmark is ca 5 W/m² (10% of 50 W/m²: 20 l/m² h @ 2.5 kWh/m³).

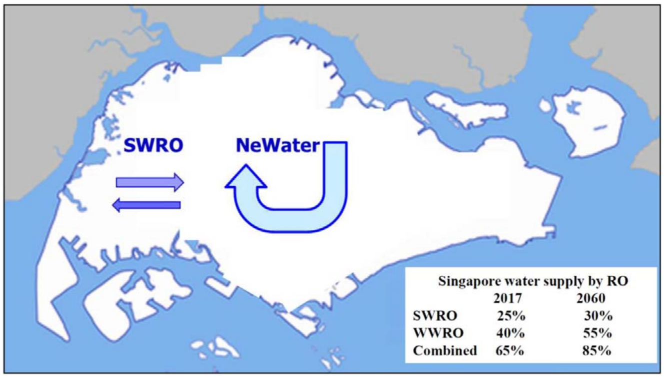


Fig. 6. Singapore is an exemplar of RO applied to SWRO desalination and wastewater RO reclamation (WWRO): Note WWRO > SWRO (source: Our Water. Our Future, PUB 2017).

opportunities via FO and PRO processes combined with seawater RO desalination. This approach has been described in several studies, for example [36,37,38]. The hybrid arrangements are;

(i) FO pretreatment where wastewater RO (WWRO) reclamation brine dilutes seawater (the FO draw), thereby lowering the osmotic pressure of the SWRO feed; and

(ii) PRO post treatment where osmotic power is recovered from SWRO brine combined with WWRO brine. Table 3 summarizes the potential energy benefits and the technical challenges of these hybridisations. In terms of the challenges the partial wastewater origin of the FO-RO hybrid means that the process is direct (or indirect, depending on buffer storage) potable reuse. However any impact would be attenuated by the fact that the final product water will have passed through two TFC barriers (the FO and the RO). The extra foot print and capital have to be traded off against the decarbonisation achieved. Fouling due to the use of WWRO brine is a significant challenge [38,39]. The key foulants from this type of feed are organic humic macromolecules and inorganic nano-colloidal calcium phosphate, due to the conventional activated sludge process (CASP) and UF origin. A number of developments could alleviate this PRO fouling including use of dual skinned membranes [40], pH adjustment and pressure-assisted osmotic backwash [39] and NF pretreatment [41,42]. The benefit of the NF barrier is that it can effectively remove humics and nanocolloids although it would add additional energy unless it is incorporated into a NF MBR in lieu of the CASP/UF stages. The NF MBR could bring added benefits in terms of higher recovery in the wastewater reclamation step [43]. This highlights the need to evaluate the water-energy relationship on a holistic basis. A further challenge is that the hybrid processes, as described, are predicated on co-location of the SWRO and suitable impaired water, such as WWRO brine, as available in Singapore (Fig. 6) and potentially in other regions where new desalination plant can locate near existing wastewater facilities (California, China etc.). A final comment concerns the relative availability of the WWRO brine, as efforts are made to increase recovery (to > 75%) in the reclamation process. This highlights the need to aim for substantially more water reuse than desalination in a given location. It would also be of interest to evaluate the use of advanced primary treated effluent as the low salinity stream, subject to improved fouling control strategies.

2.4. Overall potential

If the strategies discussed in the previous sections are combined the production of water by RO desalination could be significantly decarbonised. Fig. 7 depicts the low energy desalination scenario and indicates a net energy demand of about 0.8 kWh/m^3 compared to the current bench mark of about 2.5 kWh/m^3. To achieve this significant decarbonisation will involve additional Capex, colocation and advances in membrane technology (membranes, modules, process systems) for RO, FO and PRO, as discussed above.

Although not discussed in this review, the future decarbonisation of desalination is likely to involve membrane distillation (MD) in a significant role for brine processing and local desalination, using waste heat and solar energy [3,4].

3. Alternative energy sources & a membrane-enable osmotic battery

A straight forward approach to decarbonisation is to use renewable energy [44,45]. Indeed in Australia several SWRO plant have renewable energy plant built as large-scale carbon offsets; the Sydney desalination plant has a 67 turbine wind farm offset. However an integral part of renewable energy usage is how to accommodate its intermittency. Some developments have been made to use RO membranes with intermittent or variable power (for example [46]) but the most effective approach for moderate to large scale plant would require energy storage. The major strategy for grid-scale storage is the concept of 'pumped hydro' where the intermittent renewable energy is used to replenish the water levels in a closed system hydroelectric scheme. This can be anticipated as an area of significant growth although there may be a challenge in finding the topography with sufficient hydraulic head difference.

An alternative for grid-scale storage is an osmotic battery (OB) where two reservoirs, one of high salinity brine and the other of low salinity, are connected to a PRO system [47]. The location of the OB would not be constrained by topography and could be conveniently positioned adjacent to the source of renewable energy. This section briefly discusses some of the features of an OB and preliminary considerations of process components and scale. For example, the OB could be a closed loop system with a fixed inventory of water and salt, except for minor replenishment due to losses. The two solutions could be essentially foulant free which would simplify operation and maximise performance. The OB concept is illustrated in Fig. 8.

Three issues need to be addressed, (i) battery recharge, (ii) battery energy storage and (iii) battery peak power output. The PRO process

Table 3
Hybrid process energy benefits & technical challenges: * See Appendix A for estimates.

Process	Potential energy benefit*	Challenges
Pretreatment by FO, SWRO feed dilution by WWRO brine	~0.5 kWh/m^3	• Final product water has WW origin • FO fouling by WWRO brine • Footprint and capital • Better membranes and modules • Colocation of SWRO & WWRO
Post treatment by PRO, for Osmotic power by WWRO brine/SWRO brine	~0.5 kWh/m^3	• Better membranes and modules • PRO fouling by WWRO brine • Foot print and capital • Colocation of SWRO & WWRO

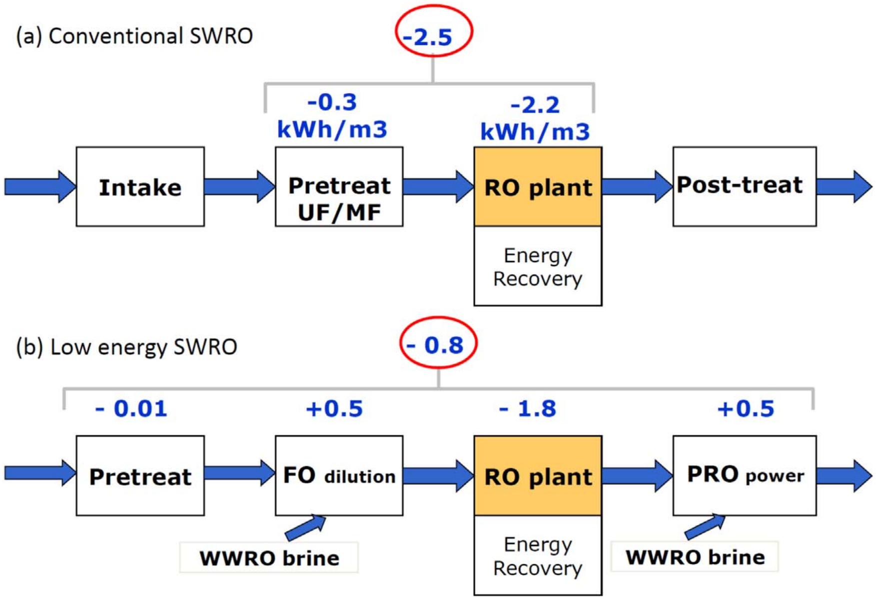


Fig. 7. Desalination process incorporating energy saving strategies: low energy pretreatment, FO dilution, UPM RO and PRO power recovery. Values are approximate kWh/m^3 of product water.

will cause dilution of reservoir 1 (high salinity source) and salt build up in reservoir 2. Battery recharge involves restoring the reservoirs to their maximum osmotic gradient where reservoir 1 has water removed and reservoir 2 has salt removed; these streams need to be transferred between reservoirs. Intermittent renewable energy would be used to drive the water/salt balancing processes. It is envisaged that RO could be used for reservoir 1 brine 'recharge' and electrodialysis for reservoir 2. Noting that the power output (kW) from PRO is proportional to (osmotic difference)^2 [48] there is a clear benefit in maximising the brine osmotic pressure (OP) in reservoir 1. However there is also a constraint to system operating pressures in the PRO and the recharge RO. Our initial proposal is an OP of 100 bar in reservoir 1 (equivalent to 2.4 M NaCl or 4 × seawater salinity). This would require the PRO to operate at 50 bar since optimum power density is at ½ the OP difference [48]. However the 'recharge' RO needs to generate a brine with 100 bar OP, and for conventional RO desalination this would require an operating pressure of the order 110 bar. To avoid this it is proposed to use a novel RO flowsheet, the counter-current membrane cascade with recycle (CMCR), that can generate a brine with an OP > the system operating pressure [49]. Estimates show that the CMCR can achieve a brine with 100 bar OP at a feed pressure < 60 bar. In other words the PRO and the recharge RO systems can be operated at pressures of 60 bar, or less. Another option for recharge is to use solar-driven MD.

In terms of storage capacity the 2.4 M draw solution and low salinity stream could provide about 0.8 kWh/m^3 of mixed streams or 1.6 kWh/m^3 of draw [50]. This is the 'module maximum' which is about 30% less than the Gibbs free energy of mixing. Allowing for further inefficiencies of 25% gives an energy capacity of ~1.2 kWh/m^3 brine. Large grid storage is > 400 MWh requiring ca 330 ml brine volume, and moderate storage of 100 MWh would require ca 80 ml volume. The power output from the PRO will depend on the net power density. There are some uncertainties in estimating this but a value of 15 to 20 W/m^2 should be feasible given the 100 bar OP difference and the non-fouling nature of the solutions. A power output of 10 MW would therefore require 0.5 to 0.7 × 10^6 m^2 of membrane. The technical and economic feasibility of the OB concept relies on optimised membrane technology, RO, PRO and electrodialysis (ED).

4. Low energy desalination for agriculture

Agriculture is the largest consumer of water and RO desalination can play a significant role. However the cost and energy demand for desalinated seawater make it a challenge for agriculture [51]. Brackish water is an alternative source and could be partially desalinated by conventional RO for salt-tolerant crops. However brackish water is also amenable to very low energy processing thanks to novel FO technology applied to available draw agents. One example is a type of fertigation using the concentrated fertilizer solution as a draw across a FO membrane; this fertilizer drawn FO (FDFO) concept has been pioneered recently by H K Shon and colleagues [52–54]. The energy demand for FDFO is about 0.1 kWh/m^3 water delivered and when combined with NF, to extend its range (by extracting dilute fertilizer solution from the

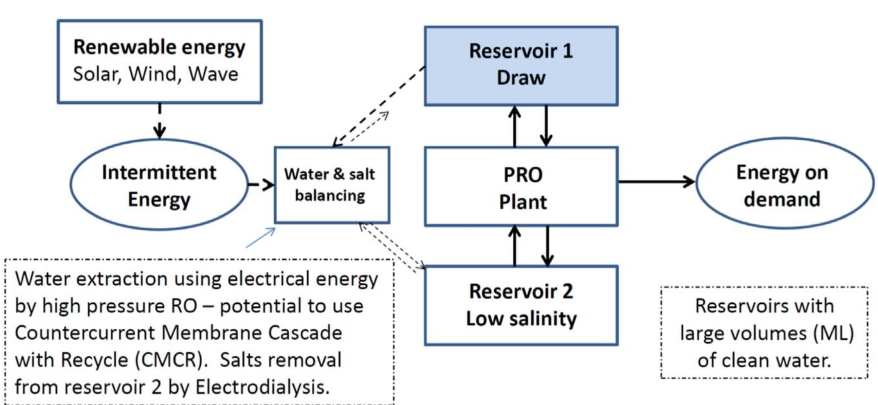
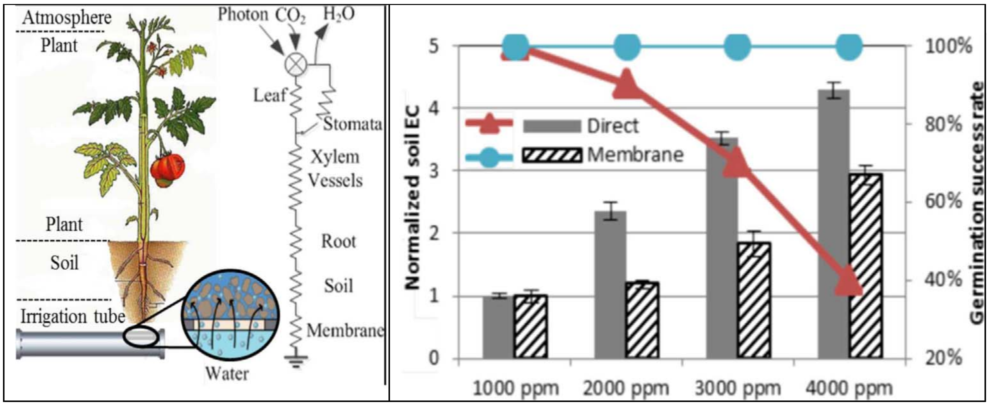


Fig. 8. An Osmotic Battery Concept incorporating PRO and energy efficient RO.



a) FOSDI concept b) Germination with FOSDI and direct irrigation

Fig. 9. (a) the FO subsurface drip irrigation (FOSDI) concept. (b) Germination success, and soil conductivity with FOSDI and direct irrigation [55,57].

recirculating draw), is about 1.0 kWh/m^3 [54]. The practical application of low energy desalination by FDFO fertigation has been demonstrated [53] and appears to have good potential.

The other example of FO-enabled irrigation has been developed by Leslie and Sutton [55]. This concept, illustrated in Fig. 9(a), uses a FO (or RO) membrane system located subsurface to deliver brackish water that is partially desalted as it is drawn through the membrane into the soil by the negative water potential (-2 to -10 bar) caused by the soil-plant root matrix. The process is forward osmosis subsurface drip irrigation (FOSDI, although it was originally referred to as ROSDI) and has the benefit that water is supplied 'on demand' to the plant roots. Since the driving force for water permeation is provided naturally the only 'desalination' energy required is that of a low pressure pump, which should be < 0.1 kWh/m^3 delivered. Fig. 9(b) shows plant germination success of 100% for FOSDI-treated plant with feed water concentrations up to 4000 ppm salt, whereas germination with direct irrigation rapidly deteriorated; soil conductivity also shows the benefit of FOSDI over direct application. The process also works with RO membranes but most success in long term trials has been with FO membranes [56,57]. More optimisation and tailoring of membrane type and process scale-up are planned.

5. Prospects and conclusions

Opportunities and strategies exist to further decarbonise membrane desalination. However each of the strategies identified involves critical challenges, as summarized below.

(i) Mitigation of biofouling requires effective pretreatment at low energy demand. This can be achieved by 'engineered biofilms' on gravity-driven low pressure membranes or in biofilters. The challenge is to improve throughput (reduce footprint) and further improve nutrient removals. Biofouling on RO membranes can also be mitigated by biomimicry using quorum quenching and dispersal agents. However long term control is elusive and may require combining these techniques with other synergistic control agents.

(ii) Improved membranes could potentially reduce energy demand by 15 to 20%. Current trends should deliver sufficient water permeability but to achieve this without increase in salt permeability is likely to need novel 'water channel' membranes; the challenge is development of effective, scaled-up and robust versions of these membranes. At the same time advances in module design are needed to provide improved mass transfer to match increases in flux. This is a very significant challenge that could involve enhanced unsteady state shear possibly facilitated by novel 'active' spacers enabled by 3D printing.

(iii) Hybridisation of SWRO with FO pretreatment and PRO post treatment using WWRO brine has the potential to achieve significant net energy savings. However the fouling of the FO and PRO is anticipated and will require very effective control strategies; some progress has been made but this needs to be optimised.

(iv) The decarbonisation of SWRO using the above strategies could be significant and potentially the net energy could be more than halved. In addition to the technical challenges of each strategy the benefit has to be traded off against the extra capital, foot print and complexity as well as process colocation.

(v) Alternative energy sources, such as renewables, provide further decarbonisation of the desalination process. The use of intermittent renewables requires grid storage and one option is the membrane-enabled Osmotic Battery (OB). Key to success of this concept is efficient 'recharge' using the CMCR RO process to restore the brine reservoir OP, and efficient discharge by the PRO process. Further work is required to select the optimum brine concentration and the PRO system design and then technical and economic demonstration.

(vi) Low energy desalination for agriculture could be achieved by FO-enabled processes. For example, forward osmosis subsurface drip irrigation (FOSDI) has the benefit of supplying water 'on demand' at very low energy input. A key challenge for this process is development of a low cost membrane specifically designed for this unique application.

(vii) The strategies and process options described could be evaluated and optimised by impact assessments that consider, inter alia, global warming potential. Methods such as Life Cycle Assessment [58,59] and Quantitative Sustainability Analysis [60] have been used for desalination.

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Appendix A. Indicative energy savings from FO dilution and PRO energy recovery

The assumed flowsheet combining SWRO and WWRO is shown as Fig. A.1.

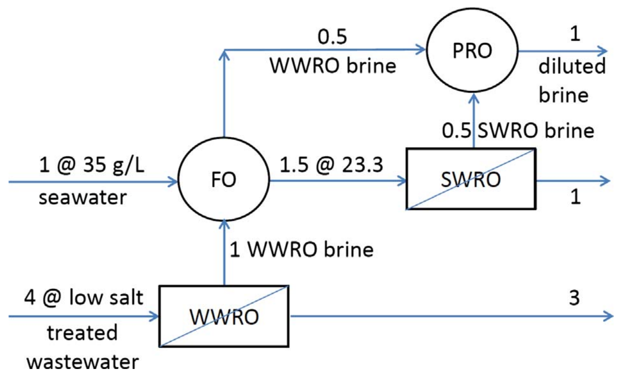

Fig. A.1. FO-RO-PRO process combining SWRO and WWRO [37].

1. FO dilution.

The FO pretreatment of the seawater provides dilution of the feed to the SWRO plant. In Fig. A.1 the feed is diluted to 23.3 g/l NaCl and undergoes 67% recovery across the RO stage. The minimum energy for this can be obtained from [1], Fig. 2(b) as ca 0.85 kWh/m^3 of product water. Assuming an actual energy of 2 × minimum gives ca 1.7 kWh/m^3. The conventional SWRO desalination step with 35 g/l feed and 50% recovery has a minimum energy of ca 1.1 kWh/m^3 and an actual energy of ca 2 × this, i.e. 2.2 kWh/m^3. Therefore the potential energy saving from pre-dilution (Fig. A.1) is ca 0.5 kWh/m^3.

2. PRO osmotic energy.

The energy obtained across the PRO process is related to the Gibbs free energy of mixing. This can be approximated by,

$$E = -\Delta G' = RT\ \ln\left(C_{\text{initial brine}}/C_{\text{mixture}}\right)$$

For initial brine volume of V_{initial} and osmotic pressure Π_{initial} this gives,

$$-\ \Delta G = V_{\text{initial}}\ \Pi_{\text{initial}}\ \ln\left(\text{dilution factor}\right)(\text{Ws})$$

For $V_{\text{initial}} = 1\ m^3$, $\Pi_{\text{initial}} = 50$ bar, dilution factor = 2, the energy = 0.98 kWh/m^3.
Assuming a PRO efficiency of ~50% the useful energy = ca. 0.5 kWh/m^3.

References

[1] M. Elimelech, W.A. Phillip, The future of seawater desalination: energy, technology, and the environment, Science 333 (2011) 712–717.
[2] N. Voutchkov, R. Semiat, N.N. Li, A.G. Fane, W.S. Ho, T. Matsuura (Eds.), Seawater Desalination, Chapter 3 in Advanced Membrane Technology and Applications, Wiley, New Jersey, 2008, pp. 47–86.
[3] G. Amy, N. Ghaffour, Z. Li, L. Francis, R.V. Linares, T. Missimer, S. Lattemann, Membrane-based seawater desalination: present and future prospects, Desalination 401 (2017) 16–21.
[4] A.G. Fane, R. Wang, M.X. Hu, Synthetic membranes for water purification: status and future, Angew. Chem. Int. Ed. 54 (2015) 3368–3386.
[5] G.K. Pearce, UF/MF pre-treatment to RO in seawater and wastewater reuse applications: a comparison of energy costs, Desalination 222 (2008) 66–73.
[6] A. Matin, Z. Khan, S.M.J. Zaidi, M.C. Boyce, Biofouling in RO membranes for seawater desalination: phenomena and prevention, Desalination 281 (2011) 1–16.
[7] T.M. Missimer, N. Ghaffour, A.H.A. Dehwah, R. Rachman, R.G. Maliva, G. Amy, Subsurface intakes for seawater reverse osmosis facilities: capacity limitation, water quality improvement, and economics, Desalination 322 (2013) 37–51.
[8] J.M. Veza, M. Ortiz, J.J. Sadhwani, J.E. Gonzalez, F.J. Santana, Measurement of biofouling in seawater: some practical tests, Desalination 220 (2008) 326–334.
[9] S.R. Suwarno, X. Chen, T.H. Chong, D. McDougald, Y. Cohen, S.A. Rice, A.G. Fane, Biofouling in reverse osmosis processes: the roles of flux, crossflow velocity and concentration polarization in biofilm development, J. Membr. Sci. 467 (2014) 116–125.
[10] M. Peter-Varbanets, F. Hammes, M. Vital, W. Pronk, Stabilization of flux during dead-end ultra-low pressure ultrafiltration, Water Res. 44 (2010) 3607–3616.
[11] E. Akhondi, B. Wu, S.Y. Sun, B. Marxer, W.K. Lim, J. Gu, L.B. Liu, M. Burkhardt, D. McDougald, W. Pronk, A.G. Fane, Gravity-driven membrane filtration as pretreatment for seawater reverse osmosis: linking biofouling layer morphology with flux stabilization, Water Res. 70 (2015) 158–173.
[12] B. Wu, S.R. Suwarno, H.S. Tan, L.H. Kim, F. Hochstrasser, T.H. Chong, M. Burkhardt, W. Pronk, A.G. Fane, Gravity-driven microfiltration pretreatment for RO seawater desalination: microbial community characterization and RO performance, Desalination 418 (2017) 1–8.
[13] S. Peldszus, C. Halle, R.H. Peiris, M. Hamouda, X.H. Jin, R.L. Legge, H. Budman, C. Moresoli, P.M. Huck, Reversible and irreversible low-pressure membrane foulants in drinking water treatment: identification by principal component analysis of fluorescence EEM and mitigation by biofiltration pretreatment, Water Res. 45 (2011) 5161–5170.
[14] G. Naidu, S. Jeong, S. Vigneswaran, S.A. Rice, Microbial activity in biofilter used as a pretreatment for seawater desalination, Desalination 309 (2013) 254–260.
[15] K.M. Yeon, W.S. Cheong, H.S. Oh, W.N. Lee, B.K. Hwang, C.H. Lee, H. Beyenal, Z. Lewandowski, Quorum sensing: a new biofouling control paradigm in a membrane bioreactor for advanced wastewater treatment, Environ. Sci. Technol. 43 (2009) 380–385.
[16] H.S. Oh, C.H. Tan, J.H. Low, M. Rzechowicz, M.F. Siddiqui, H. Winters, S. Kjelleberg, A.G. Fane, S. Rice, Quorum quenching bacteria can be used to inhibit the biofouling of reverse osmosis membranes, Water Res. 112 (2017) 29–37.
[17] R.J. Barnes, J.H. Low, R.R. Bandi, M. Tay, F. Chua, T. Aug, A.G. Fane, S. Kjelleberg, S. Rice, Nitric oxide treatment for the control of reverse osmosis membrane biofouling, Appl. Environ. Microbiol. 81 (2015) 2515–2524.
[18] N. Barraud, D.J. Hassett, S.-H. Hwang, S.A. Rice, S. Kjelleberg, J.S. Webb, Involvement of nitric oxide in biofilm dispersal of *Pseudomonas aeruginosa*, J. Bacteriol. 188 (21) (2006) 7344–7353.
[19] Y. Zhao, C.Q. Qiu, X.S. Li, A. Vararattanavech, W.M. Shen, J. Torres, C.H. Nielsen, R. Wang, X. Hu, X.A.G. Fane, C.Y. Tang, Synthesis of robust and high-performance aquaporin-based biomimetic membranes by interfacial polymerization-membrane preparation and RO performance characterization, J. Membr. Sci. 423–424 (2012) 422–428.
[20] X.S. Li, S.R. Chou, R. Wang, L. Shi, W.X. Fang, G. Chaitra, C.Y. Tang, J. Torres, X. Hu, A.G. Fane, Nature gives the best solution for desalination: aquaporin-based hollow fiber composite membrane with superior performance, J. Membr. Sci. 494 (2015) 68–77.
[21] P.S. Goh, A.F. Ismail, B.C. Ng, Carbon nanotubes for desalination: performance evolution and current hurdles, Desalination 308 (2013) 2–14.
[22] D. Cohen-Tanugi, J.C. Grossman, Water desalination across nanoporous graphene, Nano Lett. 12 (7) (2012) 3602–3608.
[23] D. Cohen-Tanugi, R.K. McGovern, S.H. Dave, J.H. Lienhard, J.C. Grossman, Quantifying the potential of ultra-permeable membranes for desalination, Energy Environ. Sci. 7 (3) (2014) 1134–1141.
[24] A. Efraty, CCD series no-19: the lowest energy prospects for SWRO through single-element modules under plug flow and closed-circuit desalination conditions, Desalin. Water Treat. 57 (46) (2016) 21696–21711.
[25] N.Y. Yip, M. Elimelech, Performance limiting effects in power generation from salinity gradients by pressure retarded osmosis, Environ. Sci. Technol. 45 (2011) 10273–10282.
[26] G.M. Geise, H.B. Park, A.C. Sagle, B.D. Freeman, J.E. McGrath, Water permeability and salt/water selectivity tradeoff in polymers for desalination, J. Membr. Sci. 369

(2011) 130–138.
[27] G.Z. Ramon, M.C.Y. Wong, E.M.V. Hoek, Transport through composite membrane, part 1: is there an optimal support membrane? J. Membr. Sci. 415–416 (2012) 298–305.
[28] J. Schwinge, Experimental and Simulation Studies of Fluid Flow and Mass Transfer in Spacer-filled Channels in Spiral Wound Modules (PhD Thesis), School of Chemical Engineering and Industrial Chemistry, University of New South Wales, 2003.
[29] J. Schwinge, P. Neal, D.E. Wiley, A.G. Fane, Estimation of foulant deposition across the leaf of a spiral wound module, Desalination 146 (2002) 203–208.
[30] F. Zamani, J.W. Chew, E. Akhondi, W.B. Krantz, A.G. Fane, Unsteady-state shear strategies to enhance mass transfer for use of ultrapermeable membranes in RO: a review, Desalination 356 (2015) 328–348.
[31] R. Guha, B. Xiong, M. Geitner, T. Moore, T.K. Wood, D. Velegool, M. Kumar, Reactive micromixing eliminates fouling and concentration polarization in reverse osmosis membranes, J. Membr. Sci. 542 (2017) 8–17.
[32] H.N.P. Dayaranthne, J. Choi, A. Jang, Enhancement of cleaning-in-place (CIP) of a RO desalination process with air micro-nano bubbles, Desalination 422 (2017) 1–4.
[33] W.S. Tan, S.R. Suwarno, J. An, C.K. Chua, A.G. Fane, T.H. Chong, Comparison of solid, liquid and powder forms of 3D printing techniques in membrane spacer fabrication, J. Membr. Sci. 537 (2017) 283–296.
[34] W.Y. Li, K.K. Chen, Y.N. Wang, W.B. Krantz, A.G. Fane, C.Y. Tang, A conceptual design of spacers with hairy structures for membrane processes, J. Membr. Sci. 510 (2017) 314–325.
[35] P. Cote, S. Siverns, S. Monti, Comparison of membrane-based solutions for water reclamation and desalination, Desalination 182 (2005) 251–257.
[36] T.Y. Cath, N.T. Hanncock, C.D. Lundin, C. Hoppe-Jones, J.E. Drewes, A multi-barrier osmotic dilution process for simultaneous desalination and purification of impaired water, J. Membr. Sci. 362 (2010) 417–426.
[37] V.S.T. Sim, Q. She, T.H. Chong, C.Y. Tang, A.G. Fane, W.B. Krantz, Strategic co-location in a hybrid process involving desalination and PRO, Membranes 3 (2013) 98–125.
[38] D.I. Kim, J. Kim, H.K. Shon, S. Hong, Pressure retarded osmosis (PRO) for integrating seawater desalination and wastewater reclamation: energy consumption and fouling, J. Membr. Sci. 483 (2015) 34–41.
[39] Q. She, L. Zhang, R. Wang, W.B. Krantz, A.G. Fane, Pressure retarded osmosis with wastewater concentrate feed: fouling process considerations, J. Membr. Sci. 542 (2017) 233–244.
[40] W. Fang, C. Liu, L. Shi, R. Wang, Composite FO hollow fiber membranes: integration of RO and NF-like selective layers for enhanced organic fouling resistance, J. Membr. Sci. 492 (2015) 147–155.
[41] C.F. Wan, T.-S. Chung, Osmotic power generation by PRO using seawater brine as draw solution and wastewater retentate as the feed, J. Membr. Sci. 479 (2015) 128–158.
[42] Y. Chen, C. Liu, L. Setiawan, Y-N. Wang, X. Hu, R. Wang, Enhancing PRO performance with low-pressure NF pretreatment: membrane fouling analysis and mitigation, J. Membr. Sci. 543 (2017) 114–122.
[43] M.F. Tay, C. Liu, B. Wu, T.H. Chong, The feasibility of nanofiltration membrane bioreactor + RO process for water reclamation: comparison with UFMBR + RO process, (2017) (submitted manuscript to Water Research).
[44] S.A. Kalogirou, Seawater desalination using renewable energy resources, Prog. Energy Combust. Sci. 31 (2005) 242–281.
[45] A. Subramani, M. Badruzzaman, J. Oppenheimer, J.G. Jacangelo, Energy minimization strategies and renewable energy utilization for desalination: a review, Water Res. 45 (2011) 1907–1920.
[46] B.S. Richards, G.L. Park, T. Pietzsch, A.I. Schafer, Renewable energy powered membrane technology: brackish water desalination system operated using real wind fluctuations and energy buffering, J. Membr. Sci. 468 (2014) 224–232.
[47] R. Mcginnis and A. Mandell, Oasys Water Inc., Utility scale osmotic grid storage, Patent EP2366066A2 (2011).
[48] K.L. Lee, R.W. Baker, H.K. Lonsdale, Membranes for power generation by PRO, J. Membr. Sci. 8 (1981) 141–171.
[49] T.H. Chong, S.-L. Loo, A.G. Fane, W.B. Krantz, Energy-efficient RO desalination: effect of retentate recycle and pump and energy recovery device efficiencies, Desalination 366 (2015) 15–31.
[50] A.P. Straub, A. Deshmukh, M. Elimelech, PRO for power generation from salinity gradients: is it viable? Energ. Environ. Sci. 9 (1) (2016) 31–48.
[51] D. Zarzo, E. Campos, P. Terrero, Spanish experience in desalination for agriculture, Desalin. Water Treat. 51 (2013) 53–66.
[52] S. Phuntso, H.K. Shon, S. Hong, S. Lee, S. Vigneswaran, A novel low energy fertilizer driven FO desalination for direct fertigation: evaluating the performance of fertilizer draw solutions, J. Membr. Sci. 375 (2011) 172–181.
[53] S. Phuntso, J.E. Kim, J. Mah, S. Hong, Z.Y. Li, N. Ghaffour, T. Leiknes, H.K. Shon, Fertilizer drawn FO process: pilot scale desalination of mine impaired water for fertigation, J. Membr. Sci. 508 (2016) 22–31.
[54] J.E. Kim, S. Phuntso, L. Chekli, S. Hong, N. Ghaffour, T. Leiknes, J.Y. Choi, H.K. Shon, Environmental and economic impacts of fertilizer drawn FO and NF hybrid system, Desalination 416 (2017) 76–85.
[55] G. Leslie, B.G. Sutton, Reverse Osmosis Irrigation, AU Pat, WO 2009105808A1, 3 Set, (2009).
[56] V.I.A. Lima, P. Le-Clech, B.G. Sutton, G. Leslie, C. Keitel, Long-term validation of a membrane-based subsurface irrigation system, IV Inovagri International Meeting, Institute for INOVAGRI Research and Innovation in Irrigated Agriculture, Fortaleza, Brazil, 2017, pp. 1–13. Available at: https://www.researchgate.net/publication/319391343_LONG-TERM_VALIDATION_OF_A_MEMBRANE-BASED_SUBSURFACE_IRRIGATION_SYSTEM.
[57] V.I.A. Lima, In-situ Desalination With Novel Membranes for Climate Resilient Irrigation (PhD Thesis), School of Chemical Engineering, University of New South Wales, 2017.
[58] J. Zhou, V.W.C. Chang, A.G. Fane, Life cycle assessment of desalination: a review on methodology, feasibility and reliability, Water Res. 61 (2014) 210–223.
[59] M. Shahabi, A. McHugh, M. Anda, G. Ho, Environmental life cycle assessment of seawater RO desalination plant powered by renewable energy, Renew. Energy 67 (2014) 53–58.
[60] N. Lior, Sustainability as the quantitative norm for water desalination impacts, Desalination 401 (2017) 99–111.